

# Modeling modern methane emissions from natural wetlands

## 2. Interannual variations 1982–1993

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**Abstract.** A global run of a process-based methane model [Walter *et al.*, this issue] is performed using high-frequency atmospheric forcing fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses of the period from 1982 to 1993. Modeled methane emissions show high regional, seasonal, and interannual variability. Seasonal cycles of methane emissions are dominated by temperature in high-latitude wetlands, and by changes in the water table in tropical wetlands. Sensitivity tests show that globally,  $\pm 1^\circ\text{C}$  changes in temperature lead to  $\pm 20\%$  changes in methane emissions from wetlands. Uniform changes of  $\pm 20\%$  in precipitation alter methane emissions by about  $\pm 8\%$ . Limitations in the model are analyzed and the effects of sub-grid-scale variations in model parameters and errors in the input data are examined. Simulated interannual variations in methane emissions from wetlands are compared to observed atmospheric growth rate anomalies. Our model simulation results suggest that contributions from sources other than wetlands and/or the sinks are more important in the tropics than north of  $30^\circ\text{N}$ . In high northern latitudes it seems that a large part of the observed interannual variations can be explained by variations in wetland emissions. Our results also suggest that reduced wetland emissions played an important role in the observed negative methane growth rate anomaly in 1992.

## 1. Introduction

Starting in mid-1983 recent changes in the global atmospheric methane concentration have been monitored by the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL). Atmospheric methane concentrations increased throughout the measurement period, but in the 1990s, the growth rate slowed from  $\sim 14$  ppbv  $\text{yr}^{-1}$  in 1984 to  $\sim 3$  ppbv  $\text{yr}^{-1}$  in 1996 [Dlugokencky *et al.*, 1998]. Superimposed on this trend is considerable interannual variation. In 1992, for example, the global methane growth rate dropped dramatically and even became negative for a short period but started to increase again in 1993. The causes for observed interannual variations and particular anomalies have not yet been fully identified. No comprehensive modeling study of the entire global methane cycle has been performed for that period, although variations in the OH sink and the wetland source [Bekki and Law, 1997], and the fossil fuel source [Law and Nisbet, 1996] have been studied. Numerous studies have been carried out to explain the strong negative growth rate anomaly in 1992 (section 3.2). It seems clear that no change in one single source (or sink) but a combination of changes in different sources and the sink was responsible for that anomaly. Until now, however, none of the

proposed scenarios has been able to fully explain the atmospheric observations.

In preindustrial times, wetlands constituted the dominant global methane source. However, since the beginning of the industrialization, methane emissions from anthropogenic methane sources increased strongly. Table 1 lists global estimates for all major methane sources reported in two different studies [Houweling *et al.*, 1999; Hein *et al.*, 1997]. The estimate by Hein *et al.* is a “top-down” derived budget employing an inverse model; the authors used atmospheric methane measurements from the NOAA/CMDL network and some a priori information about the different methane sources and sinks. The uncertainties in the different source strengths were reduced by more than a third, but they are still considerable. Houweling *et al.* [1999] report a global methane budget based on “bottom-up” estimates, i.e., emission estimates based on small-scale measurements for the different sources and (statistical) methods to extrapolate to the global scale. This budget was derived from various recent studies [Houweling *et al.*, 1999, Table 2] (and references therein) and was used as an a priori estimate for their inverse modeling study (they did not distinguish between different methane sources in their a posteriori estimate). As the differences between these two estimates reveal, the uncertainties concerning the present global methane budget are still quite large. According to current estimates, natural wetlands constitute about 25–40% of the global methane source and hence the largest single source at present. Many methane sources do not depend at all, or not very

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**Table 1.** Global Methane Sources and Sinks, Tg yr<sup>-1</sup>

	Top-Down <sup>a</sup>	Bottom-Up <sup>b</sup>
<i>Sources</i>		
Animals	90 ± 20	98 ± 40
Rice	69 ± 23	80 ± 50
Wetlands	232 ± 27	145 ± 41
Landfills	40 ± 15	48 ± 20
Biomass burning	41 ± 11	40 ± 30
Fossil sources <sup>c</sup>	103 ± 15	89 ± 45
Other sources <sup>d</sup>		58 ± 49
Total source	575	558
<i>Sinks</i>		
Tropospheric OH	469 ± 30	485 ± 25
Stratosphere	44 ± 8	40 ± 10
Soil uptake	28 ± 14	30 ± 15
Total sink	541	555

<sup>a</sup>Hein *et al.* [1997].<sup>b</sup>Houweling *et al.* [1999, and references therein].<sup>c</sup>Oil/gas production and coal mining.<sup>d</sup>Sum of fossil fuel and domestic biofuel combustion, industrial production of iron, steel, and chemicals, termites, oceans, and volcanoes.

strongly, on climate, but methane emissions from wetlands are highly climate-sensitive because they are controlled by variations in soil temperature and soil moisture.

The aim of this study is to investigate the potential role of natural wetlands in the observed interannual variations of the atmospheric methane growth rate. A global climate-sensitive process-based methane-hydrology model [Walter *et al.*, this issue] is used to study climate-induced changes in methane emissions from natural wetlands for the period from 1982 to 1993. The European Centre for Medium-Range Weather Forecast (ECMWF) reanalyses [Gibson *et al.*, 1997] are used as forcing. The model is applied to the current global wetland distribution of Matthews and Fung [1987]. This is the first study to apply a global process-based model to simulate interannual variations in methane emissions from natural wetlands. Cao *et al.* [1996] calculated present-day global methane emissions from wetlands using a process-based model to simulate methane emissions based on the amount of decomposed organic carbon, water table, and temperature. Christensen *et al.* [1996] used a process-oriented ecosystem source model to calculate present-day methane emissions from northern wetlands (>50°N) based on heterotrophic respiration. However, both models have not been applied to estimate interannual variations. Bekki and Law [1997] used a two-dimensional chemistry-transport model and a simple temperature dependence for wetland emissions to calculate the effects of variations in wetland emissions on the methane growth rate for the period 1980–1992. However, only the effects of temperature but not of changes in soil moisture on methane emissions were considered. Here we extend these modeling approaches by application of a process-based model that accounts for the effects of both temperature and soil moisture to explore interannual variations.

In section 3, interannual variations of simulated methane emissions from wetlands are compared to interannual variations in the observed atmospheric methane growth rate. In section 4 the sensitivities of simulated global methane emissions to changes in the climate input (soil temperature, precipitation, and water table) and assumptions/parameterizations in the model are examined. This leads to a discussion of possible causes for discrepancies between model results and observations which can be either due to limitations in the model

or to the contribution of other sources, and/or the sinks, or a combination of both (section 5).

## 2. Model Forcing

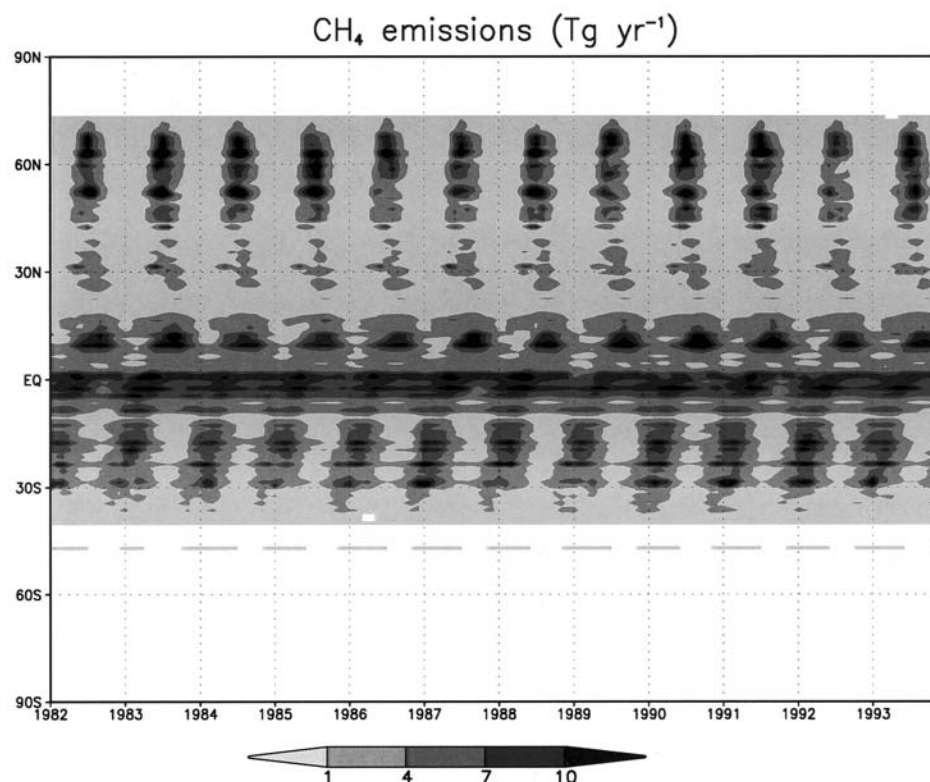
The forcing for the global methane-hydrology model is discussed in more detail by Walter *et al.* [this issue]. European Centre for Medium-Range Weather Forecast (ECMWF) reanalyses [Gibson *et al.*, 1997] for the period 1982 to 1993 are used as climate forcing. We use 24-hourly forecasts of total precipitation and soil temperature at several soil depths (4, 18, 64, and 195 cm below the soil surface, linearly interpolated to 1 cm intervals) and 6-hourly forecasts of the 2 m (air) temperature, and surface solar and thermal radiation. Daily net primary productivity (NPP) is obtained from monthly NPP values calculated by the global terrestrial carbon cycle model Biosphere-Energy Transfer and Hydrology (BETHY) [Knorr, 1997].

## 3. Results and Discussion

### 3.1. Interannual Variations During 1982–1993

Figure 1 shows the zonally integrated simulated methane emissions for the period 1982–1993. Simulated methane emissions show considerable seasonal and interannual variations. In higher northern latitudes, simulated methane emissions show a pronounced seasonal cycle with high emissions in the summer and no or very low emissions in the winter. In higher-latitude wetlands the seasonal cycle of simulated methane emissions is mainly controlled by the seasonal cycle of soil temperature; in low latitude wetlands where temperature does not change much during the year, the seasonal cycle of simulated methane emissions is dominated by the seasonal cycle of the water table. In northern low-latitude wetlands there is a dry season between February and May, and in southern low-latitude wetlands between August and November [see Walter *et al.*, this issue, Plates 2a–2d]. During the dry season the water table drops so much below the soil surface that the wetland is practically dry and methane emissions become zero. Peak methane emissions are similar in low- and high-latitude wetlands. Simulated methane fluxes vary interannually; for example, a pronounced negative emission anomaly occurs in higher northern latitudes in 1992.

Interannual variations in simulated methane emissions and their causes are further investigated, and they are compared to atmospheric observations (Figure 2). The left column of Figure 2 shows global results, while the right column shows results for the high Northern Hemisphere (HNH, >30°N). The first two rows (Figures 2a–2d) show comparisons between model results and atmospheric observations [Dlugokencky *et al.*, 1998] which started in mid-1983. The model results in Figures 2a–2d are always simulated methane emission anomalies from natural wetlands. The global observations (Figures 2a and c) are observed atmospheric methane growth rate anomalies. The “observed” anomalous methane source shown in Figures 2b and 2d, 4, 5, and 7 was inferred from the seasonally corrected and zonally averaged atmospheric CH<sub>4</sub> measurements [Dlugokencky *et al.*, 1998] by means of an inversion procedure using a simple 3-box meridional mixing model of the atmosphere divided at 30°N and 30°S. Thereby the mixing parameters of the 3-box model were determined from atmospheric measurements of sulfur hexafluoride (SF<sub>6</sub>) [Levin and Hessheimer, 1996]. The first row shows filtered (cutoff frequency: (15



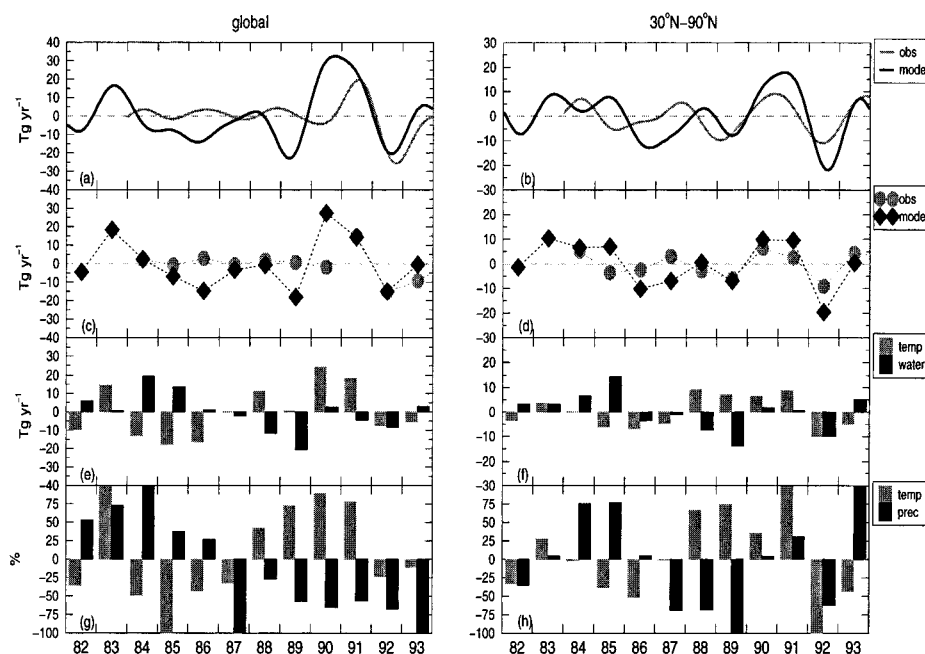
**Figure 1.** Spatial-temporal variation of simulated methane emissions ( $\text{Tg yr}^{-1}$ ) zonally integrated over  $1^\circ$  latitudinal bands.

month) $^{-1}$ , pass-through frequency: (36 month) $^{-1}$ ) monthly values and the second row annual totals. In all cases, observed atmospheric methane growth rates were detrended, assuming that the observed trend in the atmospheric methane growth rate is caused by changes in other methane sources and sinks. Recent studies indicate that global OH concentrations may have increased over the last two decades and that methane emissions are still increasing [Kroll *et al.*, 1998; Karlsdottir and Isaksen, 2000]. For example, fossil fuel emissions [Law and Nisbet, 1996], methane emissions from biomass burning [Hao and Ward, 1993], and rice paddy emissions [Shearer and Khalil, 1993; Denier van der Gon, 2000] have increased in the last decades. Estimates of methane emissions from animals and landfills also show an increase over this period [Matthews *et al.*, 1998]. Our results reveal that over the 12 year simulation period there is no trend in methane emissions from wetlands. The comparisons between model results and atmospheric observations show that the anomalies in the data and the model results are of the same order of magnitude, with the simulated anomalies being slightly larger. This could be, in part, because as discussed by Walter *et al.* [this issue], total simulated methane emissions seem to be overestimated. In a modeling study using a two-dimensional chemistry-transport model and a simple temperature dependence for wetland emissions, Bekki and Law [1997] calculated the effect of variations in wetland emissions on the methane growth rate for the period from 1980 to 1992. As they used a lower temperature sensitivity and smaller wetland source than in our study, the magnitude of their results is smaller. However, in years when water table variations are small, the patterns in their and our results are similar.

In several years, there is good agreement between model results and observations, particularly in the annual anomalies

(Figures 2c and 2d). In general, the agreement between model results and observations is better in the HNH than globally; in the HNH from 1988 to 1993, model results and observations show a similar phase behavior. Therefore our results suggest that particularly in the HNH, observed anomalies in the atmospheric methane growth rate are, to a large extent, explained by methane emission anomalies from natural wetlands. Discrepancies between model results and observations in Figures 2a–2d are either due to contributions from other sources or the sinks or due to shortcomings in the model, or any combination of these reasons. A detailed discussion of the possible causes for discrepancies between model results and observations in Figures 2a–2d is presented in section 5.

Factorial experiments were carried out to investigate and separate the impacts of anomalies in soil temperature and in water table on simulated methane emission anomalies (Figures 2e and 2f). Anomalies caused by soil temperature variations are calculated using the “mean” seasonal cycle of the water table (the mean of the 1982–1993 period) but the original soil temperature as input files for the methane model. The same approach was used for water table anomalies. In some years the effects of soil-temperature and water-table anomalies on emission anomalies are of similar magnitude but different in sign (e.g., in 1982, 1984, 1988, and 1993 in Figure 2e and in 1982, 1988, and 1993 in Figure 2f). In these years, these offsets result in small simulated anomalies. In contrast, large emission anomalies occur in years when the effect of either soil temperature or water table dominates, or when both operate to either increase or reduce emissions. In the HNH, 50% of emission variations are caused by temperature and 50% by water table variations; globally, temperature variations are responsible for about 60% of simulated variations. These results confirm that



**Figure 2.** Comparison between model results and observations, and analysis; for the whole globe (left side) and the high Northern Hemisphere (HNH,  $>30^{\circ}\text{N}$ ) (right side). Row 1, comparison between filtered simulated monthly methane emission anomalies from wetlands (black) and filtered observed monthly atmospheric growth rate anomalies (grey) ( $\text{Tg yr}^{-1}$ ) (transport is considered; see text); row 2, comparison between simulated annual methane emission anomalies from wetlands (black) and observed annual atmospheric growth rate anomalies (grey) ( $\text{Tg yr}^{-1}$ ) (transport is considered; see text); row 3, results from a factorial experiment separating the influences of temperature (grey) and water table (black) anomalies on simulated methane emission anomalies ( $\text{Tg yr}^{-1}$ ); row 4, temperature (grey) and precipitation (black) anomalies (%) relative to the 1982–1993 mean, annual mean (global, left side), and May–October mean (HNH, right side). Note that y-axis units differ for global and HNH results.

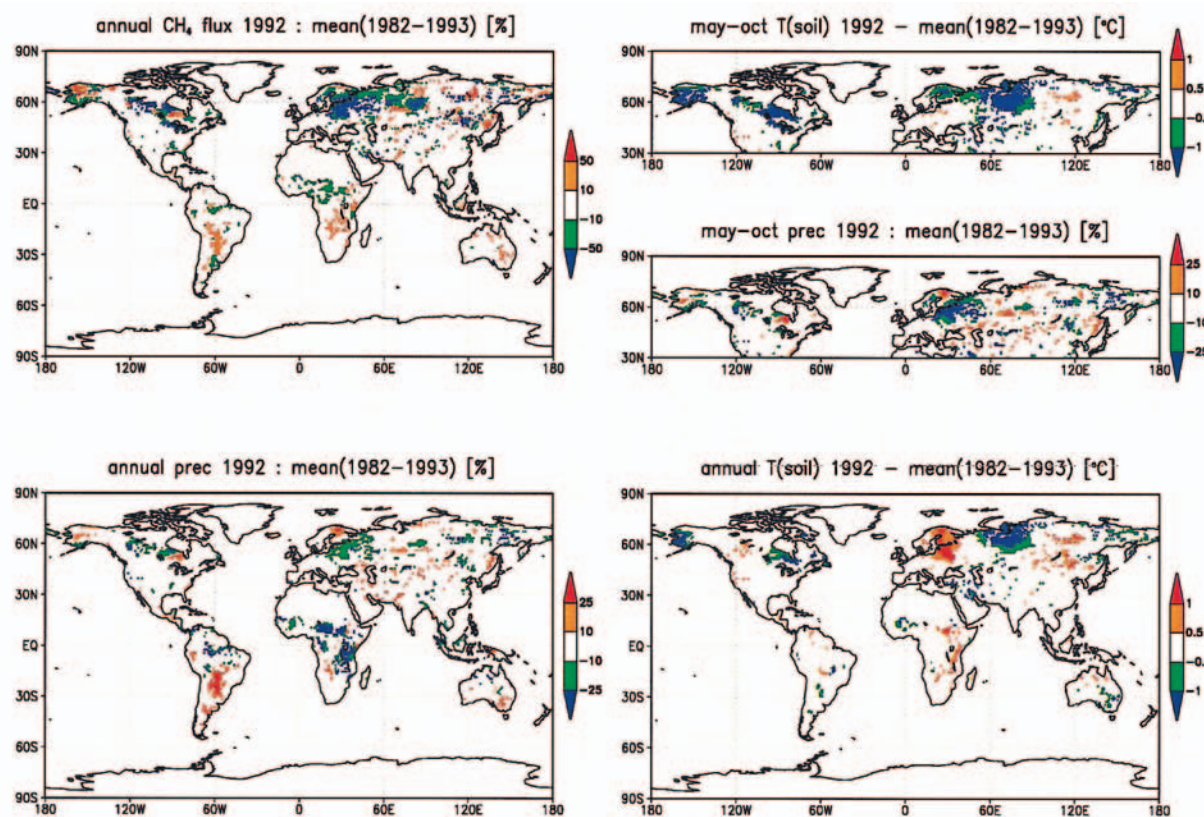
precipitation anomalies strongly influence our modeling results. Hence inclusion of precipitation is important for modeling methane emission anomalies from wetlands.

Figures 2g and 2h show anomalies (percent) (relative to the respective maximum anomalies of the period 1982–1993) in soil temperature and precipitation, which are input data of the global methane-hydrology model [Walter *et al.*, this issue]. Figure 2g shows annual temperature and precipitation anomalies, Figure 2h anomalies for May–October, which is approximately the period of the productive season in the HNH (see Figure 1). The response of the methane model to changes in temperature is almost instantaneous if the water table remains unchanged [Walter *et al.*, 1996; Walter and Heimann, 2000]. The response of the hydrologic model to changes in precipitation is more complex, since water is stored in soil. However, more precipitation generally leads to higher water tables [see Walter *et al.*, this issue, Figure 5 and Plate 2f]. So in almost all cases, temperature and precipitation anomalies, respectively, translate into temperature-dependent and water table-dependent emission anomalies of the same sign (compare Figure 2, rows 3 and 4). The reasons for differences between input data anomalies and the results in the factorial experiments are as follows: (1) the synchronicity of the anomalies in temperature and precipitation can affect results; for example, temperature anomalies translate into emission anomalies only during the productive season; (2) if a negative precipitation anomaly is large and causes a large negative water-table anomaly, a coincident temperature anomaly does not strongly impact methane emission (for example, Figure 2g, 1987 and 1989).

### 3.2. The 1992 Growth Rate Anomaly

Plate 1 (top, left) shows a global map of simulated annual methane emission anomalies (%) for 1992 relative to the 1982–1993 mean. Plate 1 (top, right) shows May–October temperature ( $^{\circ}\text{C}$ ) and precipitation (%) anomalies for 1992 relative to the 1982–1993 mean for the HNH only; in Plate 1, bottom, annual precipitation (%) and temperature ( $^{\circ}\text{C}$ ) anomalies for 1992 relative to the 1982–1993 mean are plotted. In 1992 productive season (May–October) temperature anomalies are negative almost throughout all HNH wetlands, and simulated methane emission anomalies are negative in most of the HNH wetlands. Those regions in the HNH, however, where simulated methane emission anomalies are positive are regions where May–October precipitation anomalies are positive (Alaska, Hudson Bay, parts of Siberia). In the tropics, temperature anomalies are generally small in 1992 and simulated methane emission anomalies occur in regions with precipitation anomalies. Therefore the large simulated negative methane emission anomaly in the HNH in 1992 is caused by the large negative temperature anomaly after the eruption of Mount Pinatubo that coincides with a large negative precipitation (and hence water table) anomaly (see also Figure 2f); that is, the large extent of this anomaly is caused by the coincidence of large negative temperature and precipitation anomalies and cannot be explained by temperature variations alone. The methane model, however, overestimates the magnitude (Figure 2d) in the HNH. This could be explained by (1) the fact that the methane model overestimates total annual global





**Plate 1.** (top, left) Simulated annual methane emissions for 1992 relative to the 1982–1993 mean (%); (top, right) high Northern Hemisphere ( $>30^{\circ}\text{N}$ ) May–October temperature ( $^{\circ}\text{C}$ ) and precipitation (%) for 1992 relative to the 1982–1993 mean; (bottom, left) annual precipitation (%) for 1992 relative to the 1982–1993 mean; (bottom, right) annual temperature ( $^{\circ}\text{C}$ ) for 1992 relative to the 1982–1993 mean.

methane emissions as discussed by *Walter et al.* [this issue]; by (2) the fact that the effect of microtopography on sub-grid-scale hydrology is not considered in the model (section 4.2, Figure 4); or (3) by an increase in (an) other HNH source(s) or a decrease in the HNH sink.

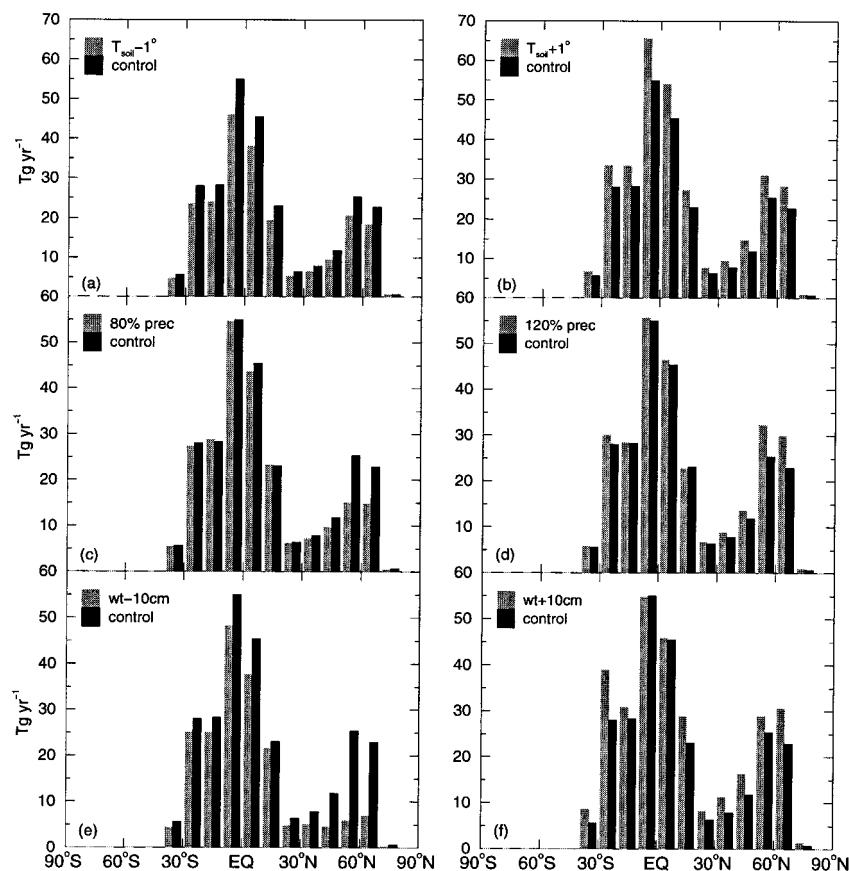
In the HNH the 1992 anomaly is the largest in the model results and in the data. Therefore our model results strongly suggest that reduced methane emissions from HNH wetlands largely contributed to that anomaly. A large contribution of northern wetlands was proposed earlier by *Hogan and Harris* [1994].

After the eruption of Mount Pinatubo, decreased tropospheric temperatures were observed [*Dutton and Christy*, 1992] along with increased stratospheric temperatures [*Labitzke*, 1994] and decreased stratospheric O<sub>3</sub> [*Gleason et al.*, 1993]. On the basis of these observations, *Bekki et al.* [1994] proposed that increased atmospheric OH concentrations caused by stratospheric O<sub>3</sub> depletion could partly explain the 1992 anomaly. *Schaffler and Daniel* [1994] suggested the subsidence of stratospheric air masses because of increased stratospheric circulation caused by increased stratospheric temperature. Both scenarios would cause a decreased methane growth rate and a positive  $\delta^{13}\text{C}$  anomaly. Since wetlands are isotopically light ( $-67$  to  $-53\text{‰}$ , the global mean  $\delta^{13}\text{C}$  is  $-47\text{‰}$  [*Quay et al.*, 1991, and references therein]), a reduction in the wetland source alone would also cause a small positive  $\delta^{13}\text{C}$  anomaly.

On the basis of data showing a negative  $\delta^{13}\text{C}$  anomaly, *Lowe et al.* [1997] suggest a large reduction (of about  $20\text{ Tg yr}^{-1}$ ) in

a very heavy source (biomass burning ( $-32$  to  $-24\text{‰}$ ) [*Quay et al.*, 1991, and references therein]); *Gupta et al.* [1996] propose a combination of increased emissions from light sources (rice paddies, animals, and landfills) and decreased emissions from heavy sources (biomass burning, fossil fuel). *Dlugokencky et al.* [1994] also suggested reduced fossil fuel emissions from the former Soviet Union (FSU) as a cause for the 1992 anomaly. However, until now the global and temporal coverage of isotopic measurements is sparse, and data sets of atmospheric methane isotopes do not agree particularly for the early 1990s and 1992 [*Francey et al.*, 1999; I. Levin, personal communication, 2000]. *Lowe et al.* [1994] and *Tyler et al.* [1993] find a negative  $\delta^{13}\text{C}$  anomaly, while *Etheridge et al.* [1998] report only a “short stabilization”; *Quay et al.* [1999] do not find a negative  $\delta^{13}\text{C}$  anomaly in 1992 at all. Therefore isotopic data do not currently seem to constitute a strong constraint on proposed scenarios, and further work is necessary to resolve that discrepancy.

Furthermore, because proposed scenarios must be consistent with atmospheric data, it is necessary to justify suggested changes in sources. For example, not much is known about methane emissions from biomass burning and its interannual variations; indications for a decreased global biomass burning source in 1992 are sparse and restricted to very few regions (e.g., Amazon region [*Artaxo et al.*, 1994], Kruger National Park (W. Trollop in the work of *Rudolph* [1994])). Increased emissions from rice paddies, animals, and landfills as proposed by *Gupta et al.* [1996] were only very small in 1992 [*Matthews et*



**Figure 3.** Sensitivity tests to climate input. Comparisons of zonally integrated annual mean methane emissions from wetlands ( $\text{Tg yr}^{-1}$ ) between sensitivity tests (grey) and control runs (black). (a,b) Sensitivity test of the global methane model to uniform changes in soil temperature of  $\pm 1^\circ$ ; (c,d) sensitivity test of the global methane-hydrology model to uniform changes in precipitation of  $\pm 20\%$ ; (e,f) sensitivity test of the global methane model to uniform changes in water table of  $\pm 10$  cm.

*al.*, 2000]. In addition, as stated by *Bekki and Law* [1997], proposed scenarios should be tested against the entire atmospheric methane record. The increase in methane growth rate after 1992, for example, makes a large reduction of gas leaks in the FSU, as suggested by *Dlugokencky et al.* [1994], unlikely. In the future, using a three-dimensional model could improve our understanding of the causes of the 1992 anomaly. However, this study emphasizes the influence of HNH wetlands to the 1992 anomaly.

## 4. Sensitivity Tests

### 4.1. Sensitivity to Climate Input

Figure 3 shows results of sensitivity tests of the global methane model to changes in soil temperature (Figures 3a,3b) and water table (Figures 3e,3f) and of the global methane-hydrology model to changes in precipitation (Figures 3c,3d). The sensitivity tests were performed for 1 year (1988, for no particular reason). Table 2 summarizes the changes in simulated annual global methane emissions (%) due to changes made in the input data.

The sensitivity of the global methane model to  $\pm 1^\circ\text{C}$  changes in surface temperature was tested. For that purpose the soil temperature of the upper soil (until 20 cm soil depth) was uniformly changed by  $\pm 1^\circ\text{C}$ . To be more realistic, the change is linearly decreased from  $1^\circ\text{C}$  to  $0.75^\circ\text{C}$  between 20

and 60 cm soil depth and from  $0.75^\circ\text{C}$  to  $0.5^\circ\text{C}$  between 60 and 150 cm soil depth. Methane production and oxidation are the major temperature-dependent processes in the methane model, the temperature dependence of production being much stronger ( $Q_{10} = 6$ ) than that of oxidation ( $Q_{10} = 2$ ) [*Walter and Heimann*, 2000]. A  $1^\circ\text{C}$  increase in temperature increases simulated global annual methane emissions by 20%, and a  $1^\circ\text{C}$  decrease in temperature reduces simulated global annual methane emissions by 17% (Table 2). Figures 3a and 3b show that these changes in simulated annual methane emissions are generally independent of the latitude and hence the environmental conditions. These results agree well with results of sensitivity tests performed with the one-dimensional methane model at different sites representing a variety of environmental conditions [*Walter and Heimann*, 2000]. At all sites,  $\pm 1^\circ\text{C}$  changes in temperature resulted in about  $\pm 20\%$  changes in

**Table 2.** Sensitivity of Simulated Annual Methane Emissions to Climate Input

	Change (%) Due to "Minus"	Change (%) Due to "Plus"
Soil temperature $\pm 1^\circ\text{C}$	-17	+20
Precipitation $\pm 20\%$	-9	+8
Water table $\pm 10$ cm	-27	+17

simulated methane emissions. This is a stronger response than obtained by *Cao et al.* [1998] and earlier studies using regression models [Öquist and Svensson, 1996], however, field observations showed an up to fourfold–fivefold increase in methane emissions if temperature increased by 4°C [Öquist and Svensson, 1996]. These results give an idea of how large changes in methane emissions from natural wetlands can be under a changed climate. To make a more realistic estimate of the increase in methane emissions from natural wetlands owing to a possible global warming, however, one needs to use GCM output from a global change scenario experiment as input for the methane-hydrology model.

In the global methane-hydrology model, uniform changes in precipitation of +20%/–20% lead to changes in simulated global annual methane emissions of +8%/–9%, respectively (see Table 2 and Figures 3c,3d). Twenty percent changes in precipitation have a much larger effect in higher latitudes; sensitivity tests with the hydrology model show that 20% changes in precipitation have a stronger effect on the seasonal cycle of the simulated water table in the HNH [see *Walter et al.*, this issue, Figure 5]. In the tropics during the dry season, precipitation is very low, and therefore a 20% change does not have a large effect; during the wet season, tropical precipitation is extremely high, causing standing water, and a change in precipitation of 20% changes runoff, but not the water table, in the hydrologic model. As discussed by *Walter et al.* [this issue], the parameterization of lateral inflow,  $L$ , in the hydrologic model leads to the problem that in some low-latitude wetlands the water table is slightly higher in years with lower precipitation, and vice versa (20°S and 20°N). This sensitivity test provides a range for possible variations in methane emissions from natural wetlands if precipitation changes under a changed climate.

In the global methane model, uniform changes in the water table of +10 cm/–10 cm change simulated global annual methane emissions by +17%/–27%, respectively. As with precipitation, the effect of a changed water table is, in general, larger at higher latitudes. Simulated methane emissions are not affected by the depth of standing water; only changes in the water table below the soil surface affect simulated methane emissions. In the hydrologic model, owing to runoff, standing water rarely exceeds a depth of 10 cm [see *Walter et al.*, this issue, Figure 4]. For that reason, lowering the water table by 10 cm has a larger effect on simulated global annual methane emissions than raising it by 10 cm. Particularly at higher latitudes, the water table is often below the soil surface during the productive season; there, lowering the water table by 10 cm means increasing the oxic top soil by 10 cm. At 10°S, simulated methane emissions are slightly smaller than in the control run if the water table is changed by +10 cm. Sensitivity tests with the one-dimensional model have shown that this can happen in only one situation [Walter, 1998]. If the water table falls below the soil surface during the productive season, when top soil methane concentrations are high, there is initially a peak in diffusive methane flux. This peak can be so high that for a short time (a few days) simulated fluxes are higher if the water table falls below the soil surface than if it stays above the soil surface. These results show that the response of the methane model to a changed water table is quite nonlinear. Therefore the correct calculation of the water table is crucial for simulating methane emissions from wetlands. The further development of the hydrologic model or a model that can account for subgrid vari-

ations in the water table is thus a priority for improving global modeling of emissions from natural wetlands.

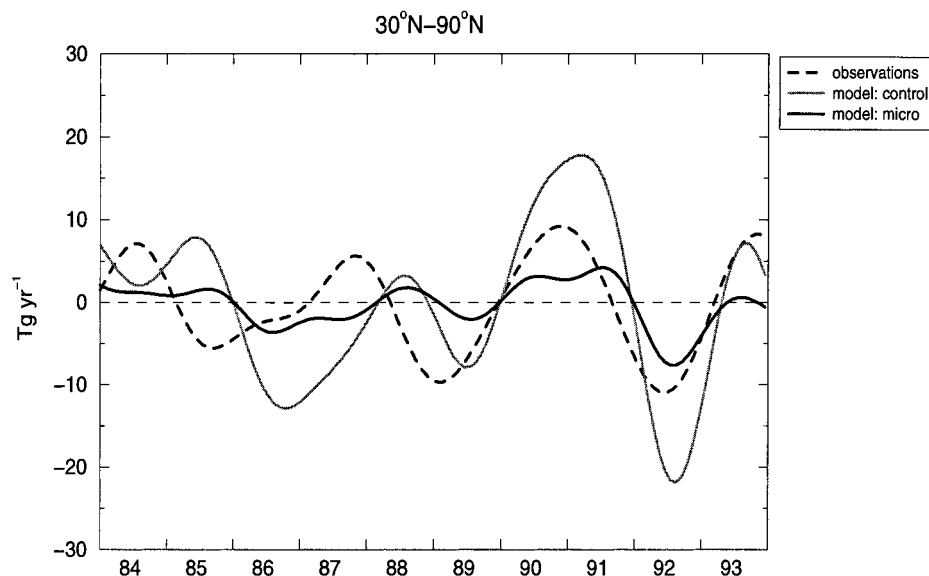
#### 4.2. Sensitivity to Assumptions in the Global Methane-Hydrology Model

The following four assumptions and parameterizations made in the global methane-hydrology model are tested: (1) The “mean” water table is used for a grid cell; that is, subgrid variations in wetland elevation and hence hydrology are neglected; (2) the  $Q_{10}$  factor used to describe the temperature dependency of processes leading to methane production (which are production of substrate for methanogenesis and methane production itself) is globally set to 6; (3) globally, a maximum methane oxidation rate of 20  $\mu\text{M h}^{-1}$  is used; (4) the effect of the parameterization of the lateral inflow,  $L$ , in the hydrologic model on simulated interannual variations in methane emissions from tropical wetlands is assessed.

1. Usually, a wetland has a microtopography with holes (hollows) and areas elevated several tens of centimeters relative to the overall wetland surface (hummocks). As a consequence, the position of the water table relative to the soil surface is not constant throughout the wetland. A difference in the water table of a few tens of centimeters, however, can change methane emissions considerably. Since the water table calculated by the hydrologic model is considered to be the mean water table of the wetland, certain parts of the wetland have a higher water table, others have a lower water table. The following sensitivity test (“micro”) is carried out to test how a more realistic treatment of the water table affects the modeling results. It is assumed that in 60% of the wetland area of each grid cell the water table is the mean water table as calculated by the hydrologic model, 10% are hollows that are water-filled throughout the year, and the remaining 30% are hummocks or areas that are sufficiently elevated that methane emissions are zero. Figure 4 shows the results of the micro sensitivity test for the HNH (it is not expected that microtopography has a large effect in the tropics, because during the wet season, there is usually standing water). As in Figure 2b, simulated interannual methane emission anomalies from wetlands are compared to observed atmospheric methane growth rate anomalies. Figure 4 shows that the micro assumption leads to smaller amplitudes in the model results. As methane emission anomalies may be overestimated in the control run, the amplitudes in the micro run are more comparable to amplitudes in the observations. Particularly in 1992 the micro run gives a better result. However, at times when model results (in the control run) and observations are out of phase, the micro assumption does not improve this. To take sub-grid-scale microtopography into account, a hydrologic model to calculate the spatial (and temporal) variation of the water table within a 1° by 1° grid cell using a high-resolution global topographic data set as, for example, in the TOPMODEL approach [Stieglitz *et al.*, 1997], will need to be developed.

2. Observed  $Q_{10}$  values for the processes leading to methane production (production of substrate for methanogenesis and methane production itself) lie in the range from 1.7 to 16 [Dunfield *et al.*, 1993; Valentine *et al.*, 1994; Westermann, 1993]. Particularly in tropical rice paddies, a low-temperature dependence ( $Q_{10}$  of the order of 2) of methane production has been observed (H.-U. Neue, personal communication, 1998). Therefore a sensitivity run using globally a  $Q_{10}$  of 2 (instead of 6) is carried out. We do not expect that a  $Q_{10}$  of 2 will improve the results in the HNH; in all tests of the model in HNH wetlands



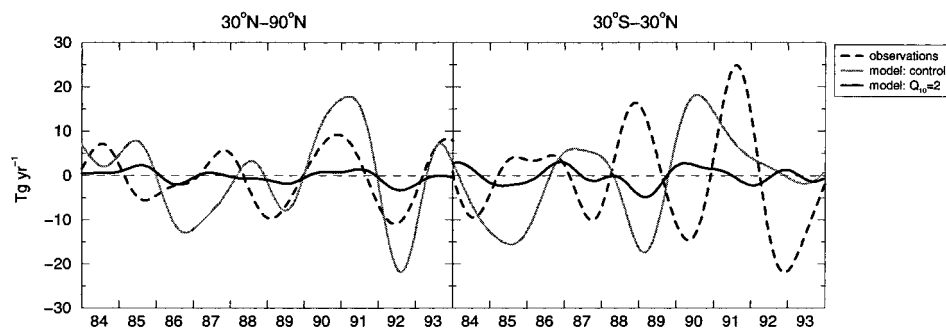


**Figure 4.** Sensitivity test to the effect of including microtopography. Filtered simulated monthly methane emission anomalies from the micro run (black; see text) are compared to the control run (grey) and to the filtered observed anomalous methane growth rate (dashed) for the high Northern Hemisphere ( $>30^{\circ}\text{N}$ ) ( $\text{Tg yr}^{-1}$ ) (transport is considered; see text).

(using  $Q_{10} = 6$ ) the amplitudes of simulated temporal variations of methane emissions (which are mainly temperature driven) agreed well with observations. In the tropics, however, the methane model was tested against only one data set from a site that was not suitable for testing the  $Q_{10}$  of methane production, because the seasonal temperature variation was only  $2^{\circ}\text{C}$  (and the seasonal pattern of methane emissions was mainly influenced by the seasonal pattern of the water table) [Walter and Heimann, 2000]. Figure 5 shows simulated methane emission anomalies for the  $Q_{10}$  sensitivity test ( $Q_{10} = 2$ ) and the control run ( $Q_{10} = 6$ ) compared to observed anomalies in the atmospheric methane growth rate (as in Figure 2b, a simple 3-box model is used to obtain the “observed” anomalous methane source) for the HNH and the tropics, respectively. In the  $Q_{10}$  sensitivity test, the amplitude of results is considerably lower than in the control run and also much lower than in the observations. Hence a low  $Q_{10}$  of 2 for methane production in the model does not improve the results. In the tropics, where in many years the model (control run) and the

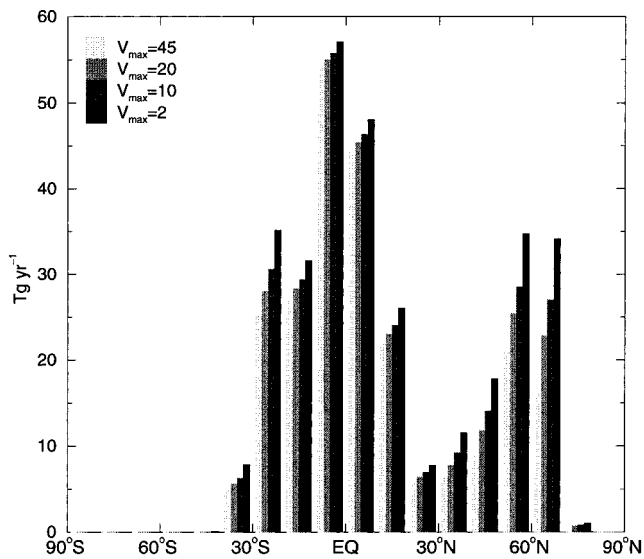
observations are out of phase, the same occurs in the  $Q_{10}$  sensitivity test, one exception being the year 1988 where the phase in the  $Q_{10}$  sensitivity test is now the same as in the observations. Therefore the model ( $Q_{10} = 6$ ) does not seem to be overestimating the impact of temperature versus the impact of water table on simulated methane emissions. In contrast however, studies using a “top-down” approach to model the global atmospheric methane cycle need smaller  $Q_{10}$  values of 2 [Houweling et al., 2000; Fung et al., 1991] or even 1.5 [Hein et al., 1997] for wetland emissions, which is still an unresolved discrepancy.

3. In the tests with the one-dimensional model, a  $V_{\text{max}}$  value (maximum methane oxidation rate in oxic soil) of  $20 \mu\text{M h}^{-1}$  was used at most test sites, the range of used  $V_{\text{max}}$  values lying between 3 and  $45 \mu\text{M h}^{-1}$  [Walter and Heimann, 2000]. Therefore a  $V_{\text{max}}$  value of  $20 \mu\text{M h}^{-1}$  is globally used in the methane model. In the  $V_{\text{max}}$  sensitivity test, global  $V_{\text{max}}$  values of 2, 10, 20, and  $45 \mu\text{M h}^{-1}$  are compared (Figure 6). Model runs using a larger  $V_{\text{max}}$  yield smaller methane emissions,



**Figure 5.** Sensitivity test to the temperature sensitivity ( $Q_{10}$ ) of methane production. Filtered simulated monthly methane emission anomalies from the “ $Q_{10} = 2$ ” run (black; see text) are compared to the control run ( $Q_{10} = 6$ , grey) and to the filtered observed anomalous methane growth rate (dashed) for the high Northern Hemisphere ( $>30^{\circ}\text{N}$ , left side) and the tropics ( $30^{\circ}\text{S}–30^{\circ}\text{N}$ , right side) ( $\text{Tg yr}^{-1}$ ) (transport is considered; see text).



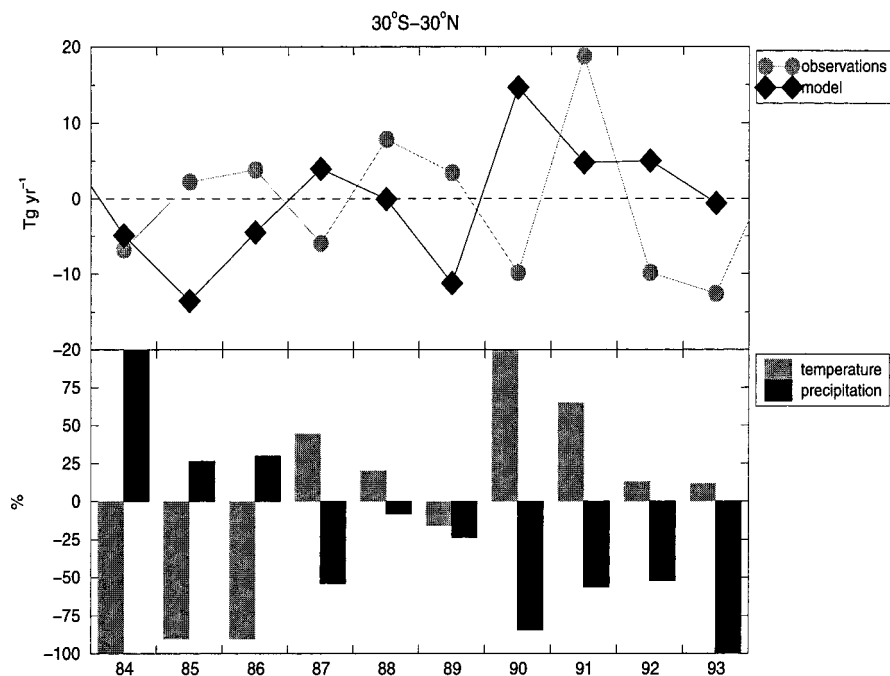


**Figure 6.** Sensitivity test to the maximum methane oxidation rate,  $V_{\max}$ . Zonally integrated annual mean methane emissions from wetlands ( $\text{Tg yr}^{-1}$ ), for runs using different  $V_{\max}$  compared to the control run ( $V_{\max} = 20$ ).

because more methane is reoxidized in soil. Figure 6 shows that the meridional pattern of simulated annual methane emissions does not change significantly if  $V_{\max}$  is changed. However, the relative changes are bigger in higher latitudes, indicating that a larger proportion of produced methane is reoxidized in soil than in the lower latitudes [see also *Walter et al.*, this issue, Plate 3d]. The patterns of interannual variations in simulated methane

emission anomalies are the same for the four runs (not shown). Therefore the choice of  $V_{\max}$  cannot explain any differences in the patterns of interannual variations between simulated methane emission anomalies from wetlands and observed atmospheric methane growth rate anomalies.

4. As shown by *Walter et al.* [this issue], in some tropical wetlands the parameterization of  $L$  leads to the unrealistic result that the annual mean water table is lower in years with higher precipitation, and vice versa. Figure 7 (top) shows simulated annual methane emission anomalies from tropical wetlands compared to observed atmospheric methane growth rate anomalies for the tropics (as in Figure 2b, a simple 3-box model is used to obtain the “observed” anomalous methane source). Figure 7 (bottom) shows relative annual temperature and precipitation anomalies for tropical wetlands. An indication that the parameterization of  $L$  has a significant effect on modeling results would be, if the difference between model results and observations in Figure 7 (top) would always have the opposite sign from the precipitation anomaly in Figure 7 (bottom). In 6 out of 10 cases (1985, 1986, 1987, 1990, 1992, and 1993), model results would agree better with observations, if precipitation anomalies had a stronger impact on modeled methane emission anomalies; however, in the four remaining years the opposite is the case. Hence there is no evidence that the parameterization of  $L$  causes differences in the patterns of interannual variations in simulated methane emission anomalies from wetlands and observed atmospheric methane growth rate anomalies. So because of the fact that the problem with  $L$  occurs only at a few tropical wetlands [*Walter et al.*, this issue, Plates 2e,2f] and that it has an effect only in the dry season [*Walter et al.*, this issue, Figure 5], it does not seem to affect simulated methane emissions much.



**Figure 7.** Tropical results (30°S–30°N). (top) Comparison between simulated annual methane emission anomalies from wetlands (black) and observed annual methane growth rate anomalies (grey) ( $\text{Tg yr}^{-1}$ ) (transport is considered; see text); (bottom) annual temperature (grey) and precipitation (black) anomalies (%) relative to the 1982–1993 mean.

## 5. Interannual Variations During 1982–1993: Discussion

Figures 2, 5, and 7 compare interannual variations in simulated methane emission anomalies from wetlands with interannual variations in observed atmospheric methane growth rate anomalies. As mentioned in section 3, the general agreement between model results and observations is much better in the HNH than in the tropics; in the HNH a considerable part of observed atmospheric methane growth rate anomalies can be explained by methane emission anomalies from natural wetlands. However, possible contributions from other sources and/or the sinks and shortcomings of the model need to be assessed. On the modeling side the following points have been identified: (1) the parameterization of the lateral inflow,  $L$ , in the hydrologic model; (2) the use of only one tropical data set for testing and calibration; (3) the temperature dependency ( $Q_{10}$ ) of methane production in the methane model; (4) expansion and contraction of wetland areas is not considered; (5) microtopography effects are not considered; (6) the limited number of iterations used in the global methane model; and (7) errors in the input data. In the following, each of these points as well as the contributions from other sources and/or the sinks will be discussed.

1. The parameterization of the lateral inflow,  $L$ , in the hydrologic model is only problematic in very limited areas of tropical wetlands. As discussed in section 4.2, however, it does not contribute substantially to the difference between model results and observations in the tropics.

2. As there was only one data set covering the period of at least one season available from tropical wetlands, the one-dimensional methane model could not be tested for different tropical wetlands. It is possible that at other tropical sites, processes or controlling factors become important that are not included in the methane model, one example being turbulent diffusion in the standing water and its effect on transport and reoxidation of methane. So far, it cannot be assessed how important possible other processes are and how they could change our global modeling results. Since the agreement between model results and observations was good at the tropical test site, the methane model was considered to be applicable to all global wetlands.

3. As shown in Figure 5 using a methane production in the methane model that is less temperature-dependent (i.e., a  $Q_{10}$  of 2 instead of 6) does not improve modeling results, confirming that the impact of temperature changes on simulated methane emissions is not overestimated in the model and differences between model results and observations cannot be accounted for by this.

4. Particularly in the tropics during the transition from dry to wet (and back to dry) season wetland areas expand and contract. This is not considered in the global methane-hydrology model although seasonal climate variations do, in practice, produce seasonal changes in methane-producing areas. These expansions and contractions are expected to influence seasonal and interannual methane-emission patterns. In the model it is assumed that the wetland area given by the data set of Matthews and Fung [1987] is the maximum area of a wetland. As discussed by Walter *et al.* [this issue], the seasonality of a wetland is introduced through the seasonality of the water table; that is, in the model a tropical wetland dries in toto during the dry season and floods in toto during the wet season. A more realistic treatment of the transition between these two

extreme states is necessary but has not been possible so far. In the future we plan to use a combination of satellite data and a more complex hydrologic model that uses high-resolution topographic data to derive the seasonal and interannual variation in tropical wetland areas [Matthews *et al.*, 1999].

5. As shown in Figure 4, consideration of the effect of sub-grid-scale microtopography on hydrology can improve the results, particularly in the HNH. As the micro run was only a sensitivity test, a model to simulate the variation of the water table within a grid cell needs to be developed, in order to take the effect of microtopography more realistically into account. However, the largest differences between modeling results and observations occur in the tropics; there, the differences cannot be explained by having neglected the effect of microtopography on hydrology.

6. In the global methane model we use a standard 24 iterations to get to the equilibrium methane profile. Tests with the one-dimensional methane model showed that if the water table changes very rapidly below the soil surface, 24 iterations per day are not sufficient to achieve equilibrium. However, this error occurs only at some East Siberian and very few Canadian and Alaskan wetland points. There, the sum of calculated methane fluxes plus total oxidation exceeds calculated production by 10–20%. Because these are all regions with very low annual methane emissions [Walter *et al.*, this issue, Plate 3b], this error cannot affect variations in HNH wetland emissions very much; however, it will be fixed in the future.

7. Reanalyses comprise the best available input for an experiment, such as the one described in this study; however, they have errors which could cause errors in the modeling results. Stendel and Arpe [1997] compared reanalyzed tropical precipitation from ECMWF and National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) [Kalnay *et al.*, 1996] with the Global Precipitation Climatology Centre (GPCP) precipitation data which incorporates all suitable observations [Rudolf *et al.*, 1996]. They investigated 1988–1995 seasonal and interannual variations in tropical precipitation; both reanalysis data sets differ considerably from each other and from the GPCP data set. Particularly, over Africa and northwestern Argentina, ECMWF reanalysis precipitation seems to be unrealistic. Furthermore, the trend of decreasing tropical precipitation over land (Figure 7, bottom) seems to be questionable. A simplified version of the global methane-hydrology model that calculates methane emission anomalies from natural wetlands on the basis of precipitation and temperature anomalies (B. P. Walter, unpublished data, 2001) shows very similar results in the HNH for the period 1982–1993, whether it is forced with ECMWF or NCEP reanalyses. In the tropics, however, the results differ considerably for the different input data. These examples show that the uncertainty in the input data, particularly in tropical precipitation, is still large and can account for part of the difference between model results and observations in the tropics. As ECMWF and NCEP reanalyses have strengths and weaknesses in different regions, it might be useful to use other data sources (particularly for precipitation) to reduce these uncertainties in the future.

All major methane sources and sinks are listed in Table 1. In principle, each of them could contribute to observed interannual variations in the atmospheric methane growth rate (the trend in the atmospheric growth rate is not discussed here). The major methane sources in the HNH are wetlands, fossil fuels, landfills, and animals; in the tropics, most methane emis-

sions come from wetlands, biomass burning, rice paddies, and animals; moreover, most removal of methane by the OH sink takes place in the tropics [Hein *et al.*, 1997]. Methane emissions from animals and landfills, however, do not show large interannual variations, for example, on order of a few Tg [Matthews *et al.*, 2000]. With the possible exception of 1992 the same seems to be valid for fossil sources [Law and Nisbet, 1996]; if no big changes in the FSU are assumed, year-by-year changes in fossil sources are reported to be mostly positive, almost constant after 1984, and decline from the late 1980s; that is, they show no large interannual variations. Therefore in the HNH, wetlands seem to be the only methane source showing considerable interannual variation.

Rice paddies are mostly located in the tropics. The mechanisms leading to methane emissions from rice paddies are essentially the same as in natural wetlands, although factors controlling methane emissions are substantially altered by management practices such as fertilization and irrigation. Because the majority of methane emissions from rice paddies comes from irrigated rice paddies [Neue and Roger, 1993], methane emissions from this source are not expected to vary much with changes in precipitation, even though low precipitation can limit the supply of water, so rice fields cannot be watered properly (H.-U. Neue, personal communication, 1998). However, interannual changes in temperature can have some effect on interannual variations in methane emissions. The temperature sensitivity of methane emissions from rice paddies seems to be smaller than in our model [Sass *et al.*, 1991; Khalil *et al.*, 1998; van Bodegom and Stams, 1999], however, results differ among studies [Matthews *et al.*, 1991, and references therein]. In our model experiment (using  $Q_{10} = 6$ ), two thirds of the interannual variations in methane emissions from tropical wetlands were explained by temperature variations (in the sensitivity test assuming  $Q_{10} = 2$ , it is only one third). However, Figure 7 shows that an additional tropical methane source responding similarly to temperature as wetlands would not increase the agreement between model results and observations. As interannual changes in methane emissions from rice paddies due to changes in harvested area are also small [Matthews *et al.*, 2000; Shearer and Khalil, 1993], there is little evidence that methane emissions from rice paddies contribute much to the observed anomalies in the atmospheric methane growth rate. However, further studies are necessary.

Biomass burning is considered a relatively small methane source of about 40 Tg yr<sup>-1</sup> with a large uncertainty (Table 1). Systematic data on burned area and the amount of biomass burned in different ecosystems are still lacking [Hao and Ward, 1993]. Although satellite-derived information on the numbers of fires exists for some regions for the last 20 years, no quantitative relationships have been developed between the number of fires, area burned, biomass oxidized, and methane emitted [Levine, 1996a, 1996b]. Thus it is not yet possible to derive interannual changes in these variables. However, it seems probable that interannual variations in this methane source can be quite large because fires are controlled by climate, by anthropogenic activities, and sometimes by inadvertent spread of planned fires. Hence part of the discrepancy between model results and observations in the tropics could be explained by interannual variations in emissions from biomass burning. Further investigations of the biomass burning source by means of, for example, remote sensing, auxiliary tracers (e.g.,  $\delta^{13}\text{CH}_4$ , CO, or H<sub>2</sub>), and modeling approaches are needed to quantify

the contribution of this CH<sub>4</sub> source to the total observed interannual variation.

Bekki and Law [1997] investigated the sensitivity of the OH-sink to temperature variations from 1980 to 1992 employing a two-dimensional chemistry-transport model. Variations in OH are positively correlated with temperature changes; that is, temperature-induced variations in the OH sink affect the methane growth rate in the opposite way to temperature-induced variations in wetland emissions. A comparison between variations in the tropical growth rate due to OH variations [Bekki and Law, 1997, Figure 2] and the observed variations in the tropical growth rate (Figure 5, right) shows that the patterns are quite similar except in 1992, although the magnitude is larger in the observations. Since most methane removal is by OH in the tropics [Hein *et al.*, 1997], it seems probable that interannual variations in tropical OH do have an effect on interannual variations in the tropical methane growth rate. This could also explain part of the discrepancy between model results and observations in the tropics (Figure 5, right).

## 6. Summary and Conclusion

In this study we presented results of a global process-based, climate-sensitive methane-hydrology model for methane emissions from natural wetlands. The model was applied to the period from 1982 to 1993. Simulated methane emissions show a pronounced seasonal cycle and strong interannual variations. In higher latitudes the seasonal cycle of methane emissions is controlled by the seasonal cycle of temperature; in lower latitudes the seasonal cycle of methane emissions is controlled by the seasonal cycle of the water table. Simulated methane emission anomalies were compared to observed growth rate anomalies. Our results suggest that in the HNH, growth rate anomalies can, to a large extent, be explained by wetland emission anomalies. In the tropics, however, simulated methane emission anomalies do not compare well with observed growth rate anomalies. In the HNH, variations in temperature and water table affect interannual variations in methane emissions in equal parts; globally, the influence of temperature variations is slightly stronger (60%). The strong negative methane emission anomaly in the HNH in 1992 is caused by a negative temperature anomaly that coincides with a negative water table anomaly. Our results suggest that reduced methane emissions from HNH wetlands contributed to the observed negative growth rate anomaly in 1992 and should be considered in future scenarios explaining this anomaly.

In the present study, the realism of the modeled interannual variability was evaluated against anomalous CH<sub>4</sub> source variations inferred from an inversion of the observed atmospheric CH<sub>4</sub> growth rates based on a simple 3-box model of atmospheric mixing. A more realistic interannual inversion of the atmospheric CH<sub>4</sub> records from the global observation network [Dlugokencky *et al.*, 1998] using a comprehensive one-dimensional atmospheric transport model would be very valuable. Although such an inversion inevitably will only determine the spatiotemporal distribution of the sum of all CH<sub>4</sub> sources, it would nevertheless allow a much more stringent assessment of the predictions of the wetland model.

Sensitivity tests of the global methane-hydrology model revealed that uniform temperature changes of  $\pm 1^\circ\text{C}$  result in changes in methane emissions of about  $\pm 20\%$  independent of the latitude and environmental conditions. As this global result agrees with results obtained with the one-dimensional methane



model from different wetland sites [Walter and Heimann, 2000], it seems to be very robust. Uniform changes in precipitation by  $\pm 20\%$  alter simulated methane emissions by about  $\pm 8\%$ . These results indicate how large changes in methane emissions from wetlands can be under possible changed climatic conditions in the future. However, to assess these changes more realistically, one needs to use GCM output from a global-change scenario experiment as input for the methane-hydrology model.

To assess the role of wetland emissions in causing observed methane growth rate anomalies, shortcomings in the model and possible contributions from other sources and the OH sink to observed growth rate anomalies were analyzed. Several potential problems in the model have been identified. The one-dimensional methane model has been tested against one tropical data set only, and therefore it is possible that processes occurring in some tropical wetlands are not included in the model. Globally, a  $Q_{10}$  of 6 for methane production was used. All tests of the (one-dimensional) methane model in HNH wetlands show good agreement with data [Walter and Heimann, 2000], but it is possible that a  $Q_{10}$  of 6 is too high in tropical wetlands. Expansion and contraction of wetlands due to changes in precipitation are not considered. Neglecting this change in wetland areas could therefore affect modeling results, particularly in the tropics. A mean water table for grid cells is used, although owing to microtopography, the water table is not constant throughout the whole wetland. A sensitivity test (“micro”) revealed that considering sub-grid-scale variations in water table affects modeling results, and sub-grid-scale variations in water table need to be treated more realistically in the future. Errors in the input data are difficult to assess. Tropical precipitation seems to be the least certain input parameter. Hence using additional precipitation data sources could help reduce this problem in the future.

In the HNH the discrepancy between simulated interannual methane emission anomalies and interannual growth rate anomalies is relatively small. Our results suggest that in the HNH, variations in methane emissions from wetlands contribute largely to observed methane growth rate anomalies. In the tropics, model results and observations are out of phase most of the time. It does not seem probable that this discrepancy is due to the omission of an important process in the model. Reducing the tropical  $Q_{10}$  did not improve the agreement between model results and observations. Including variations in tropical wetland areas and reducing the uncertainties in tropical precipitation will probably improve our modeling results in the tropics. However, these factors are not likely to greatly change the asynchronous behavior of model results and observations. Therefore it seems probable that in the tropics, contributions to observed variations in the methane growth rate from other sources, such as biomass burning and/or the OH sink, are stronger than in the HNH.

To fully explain interannual variations in atmospheric data a more comprehensive study is necessary. A three-dimensional modeling study, including climate feedbacks on wetland emissions, atmospheric chemistry and transport, and knowledge about interannual variations in anthropogenic methane sources, could help clarify the results. As far as possible, not only concentration measurements but also isotopic data should be used to test the results. In addition, a time-dependent inverse modeling study could further constrain proposed scenarios for interannual variations and particular anomalies.

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